Astron. Astrophys. 114, 95–101 (1982)

ASTRONOMY AND ASTROPHYSICS

Experiences with the U.S. Naval Observatory Glass Circles

T. J. Rafferty and B. L. Klock

U.S. Naval Observatory, 34th and Mass., Ave., NW, Washington, D.C. 20390, USA

Received June 8, accepted June 15, 1982

Summary. During the past decade the U.S. Naval Observatory has acquired considerable experience in its quest for a high quality glass circle. These circles are used to determine the declination position angle of a meridian circle. The quality of the glass circle division lines were found to be superior to those of the conventional metal circle, which is an important factor when using photoelectric scanning devices to read the circle. The intent of this paper is to present the experiences with the glass circles acquired for the six-inch transit circle at the U.S. Naval Observatory. Analyses of the diameter corrections obtained with a number of glass circles are given. A method is introduced which permits the monitoring of the stability of the circles without taking an entire set of diameter corrections.

Key words: meridian circle – diameter corrections – glass circle

Introduction

The use of a glass circle on astrometric instruments, such as transit (meridian) circles, horizontal mirror transit circles, and astrolabes is not a novel idea. For more than a score of years the instruments at Greenwich and Brorfelde Observatories have employed glass circles to determine the declination position angle of their instruments. The division lines on these glass circles were engraved and filled with ink. The circles were approximately 9 mm thick with a diameter of 72.4 cm. At least one of these observatories encountered problems with the ink coming out of the divisions. Similar problems had been encountered with the traditional engraved metal circles which the U.S. Naval Observatory (USNO), as well as many other observatories, had utilized for most of the lifespan of these instruments.

During the middle 1950's through the mid 1960's many engraved metal circles were produced in the USNO Instrument Shop (Fig. 1). These circles were produced for the Lund, Ottawa, Hamburg-Bergedorf, and USNO instruments. However, by the end of the 1960s, the USNO Instrument Shop had lost its capability to produce high quality metal circles due to the retirement of key personnel.

At that time, in addition to Greenwich and Brorfelde, the only other instruments known to employ glass circles were the horizontal meridian circle at Pulkovo Observatory, and the Zeiss meridian circle in Caracas. Since then, instruments with 40 cm diameter glass circles have been installed in Sao Paulo, and most recently, the new Zeiss instrument for the Tokyo Observatory. The Zeiss circles, as well as the one at Pulkovo, were of similar construction to the Brorfelde circle which consists of a fairly thick piece of glass attached to the horizontal axis of the telescope. The circles are transparent except for the lines. Almost all these circles were graduated at 5′ intervals.

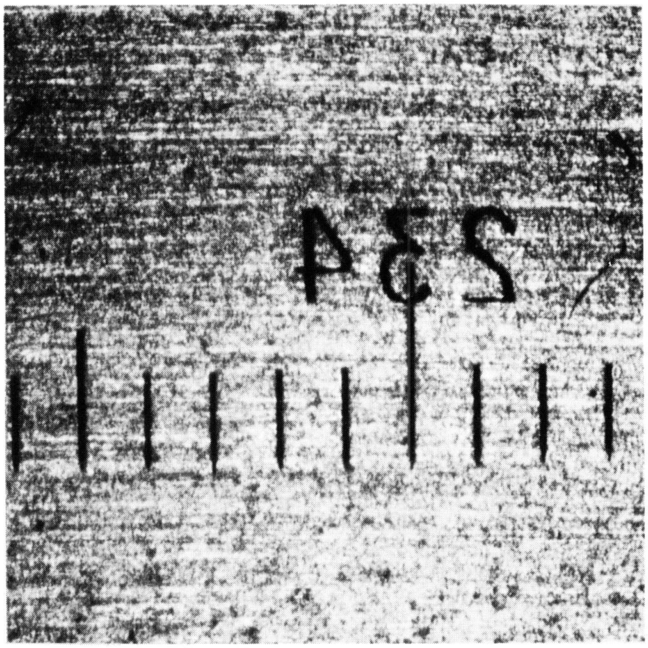

Fig. 1. Photograph of an engraved, metal circle made in the U.S. Naval Observatory instrument shop. The division lines were darkened with ink

In addition to the loss of the ability to manufacture engraved metal circles, there was another primary factor which induced the USNO to look for a new type of circle. This factor was the rapid development of the technology of automatic circle scanning systems. In 1970, the USNO awarded a contract for development of a new photoelectric scanning system for reading circles. The contractor, Watts Prototype, Inc., conducted an extensive investigation with circle samples, both metal and glass. It was soon realized that the glass circle scans were superior to the metal ones. The primary difference between the metal and glass samples was that the glass samples had better division definition then the metal samples. Also the shape of the division lines on the glass sample

Send offprint requests to: T. J. Rafferty

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **OCT 1982**	2. REPORT TYPE	3. DATES COVERED **00-00-1982 to 00-00-1982**

4. TITLE AND SUBTITLE **Experiences With The U.S. Naval Obervatory Glass Circles**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Naval Observatory,34th and Mass Ave., NW,Washington,DC,20390**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Astronomy and Astrophysics, vol. 114, no. 1, Oct. 1982, pgs. 95-101

14. ABSTRACT
It has been found in the course of U.S. Naval Observatory experience with the circles used to determine the declination position angle of a meridian circle that the quality of glass circle division lines is superior to those of conventional metal circles. Such quality is important when photoelectric scanning devices are used to read the circle. Analyses of the diameter corrections obtained with a number of the glass circles are given, and a method is introduced which allows the monitoring of circle stability without taking an entire set of diameter corrections.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

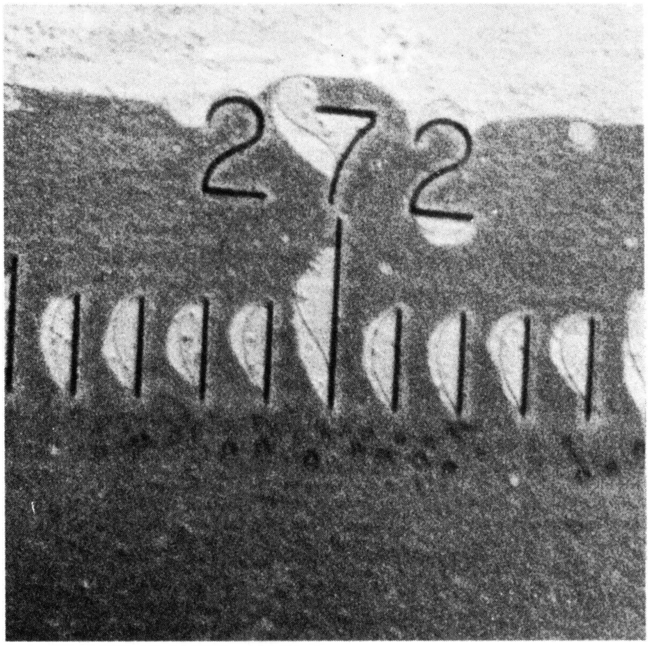

Fig. 2. Photograph of the first Teledyne-Gurley circle showing the bubbles which formed between the glass annuli six months after the circle was delivered to the USNO

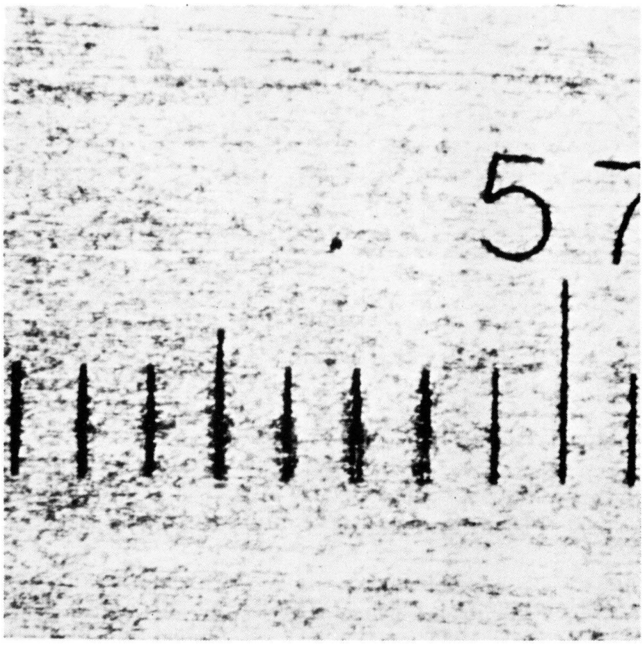

Fig. 3. Photograph of the second Teledyne-Gurley circle with the hand polished gold background showing the fading of some of the division lines

was more uniform than the metal. Due to these differences a better algorithm for determining the position of the division lines by the photoelectric scanners was developed for the glass samples. This enhanced the desire of the USNO to switch from engraved metal circles to glass circles on its transit circles. Thus the decision was made in 1971 to procure two glass circles for the six-inch transit circle. The specifications for these circles were different from any glass circle produced up to that time.

History of the Naval Observatory's Glass Circles

In 1972, the Teledyne-Gurley Corporation of Troy, New York was awarded a contract to make two glass circles for the USNO. Unlike the transparent glass circles used elsewhere, the USNO circles used the existing 68.5 cm diameter steel wheel of the six-inch transit circle as a base. The glass used had a coefficient of expansion as close as possible to that of the steel wheel. One circle consisted of a glass sandwich with one silvered glass annulus (1.5 mm thick) bonded to the steel wheel to provide a uniform, silver background. The silvered surface was roughed in such a way that it would appear similar to the background of the hand polished gold metal circles. This was done so that similar light diffusion illuminators to those used with the metal circles could also be used on the new circle. Another glass annulus (also 1.5 mm thick) had the division lines photographically deposited on the surface closest to the background annulus (i.e. the bottom surface). The second circle had a hand polished gold metal strip placed in the groove of the circle, as if it were going to be engraved. The hand polished gold also provided the diffuse background necessary for the illumination. Instead of engraving the circle, a glass annulus with divisions on its under surface (i.e. in contact with the gold inlay) was bonded to the circle. This circle appeared just like the old engraved metal circle, except that the divisions were much better defined on glass.

The process of making a glass circle proved to be much more difficult than anyone had thought. Finding a source of high quality flat glass posed a problem. Handling the delicate glass annulus proved also to be very difficult, resulting in frequent breakages. By May 1973 Teledyne-Gurley delivered its first glass circle (made of the glass sandwich with the silver background) to the USNO. The six-inch transit circle was not completely refurbished at that time and thus was not ready to start its next observing program. Consequently there was time to investigate the newly arrived circle. Scans of the glass circle showed that the diffuse illumination used with the metal circles was causing poor contrast between the background and division lines. Beam splitters were then added to provide a direct illumination which gave excellent results on the glass circle.

Slightly unequal spacing of the division lines, a characteristic of all graduated circles, makes it necessary to determine corrections for each division. To eliminate the influence of the eccentricity error which unavoidably occurs during the mounting of the circle, division lines diametrically opposite each other instead of single division lines, are measured. These measurements are referred to as "diameter corrections". A set of such diameter corrections was taken on the Teledyne-Gurley circle in April, 1973.

About six months after the first circle had arrived at the Observatory a problem began to appear with it. Bubbles were forming under the glass around the division lines. After about a week, the bubbles caused interference with the scanning of the division lines (Fig. 2). The bubbles would also show rapid changes, sometimes disappearing completely and then reappearing in a few days time. The Teledyne-Gurley engineers believed that the problem was that the glass sandwich was separating and moisture was seeping into the gaps. They believed the cause of the separation

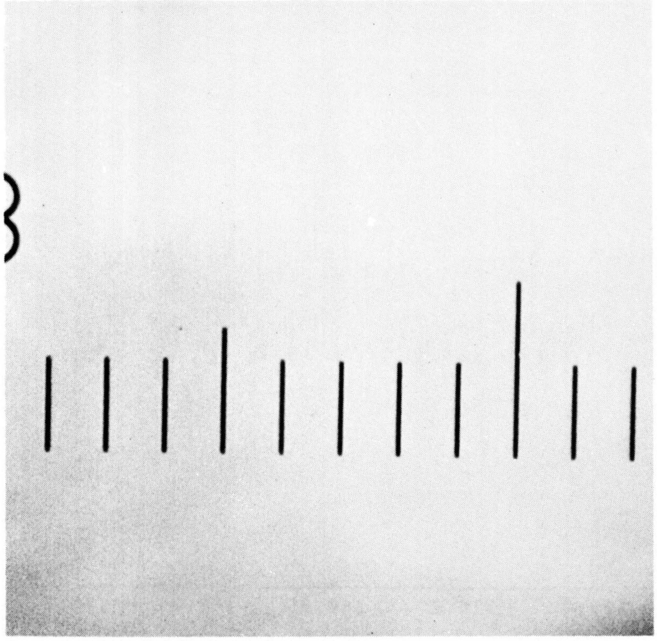

Fig. 4. Photograph of the Heidenhain circle. Note the uniform background provided by the mirror, gold finish to the circle

was due to a failure of the bonding material used to hold the two glass annuli together. They agreed to manufacture a new circle.

Meanwhile, in September of 1973, the second glass circle (with the gold background) was received from Teledyne-Gurley. Test scans showed that the beamsplitter illuminators used on the silvered background circle did not provide the contrast between the background and division lines on the rough gold background. The light diffusion illuminators used with the metal circles were then used and scans looked good. The polished gold background also did not provide the uniform background that the scan profiles with the silvered background had shown, which caused a slight degrading of the repeatability of the photoelectric scanners to determine the position of the division lines. The refurbishment of the six-inch transit circle was nearing completion in the spring of 1974. However, six months after the second circle arrived it also began to develop problems. Once again, bubbles appeared around the division lines and some division lines started to fade (Fig. 3). Scanning the circle became impossible.

Since the six-inch transit circle was nearly ready to start observing and the next Teledyne-Gurley circle was not to be delivered for nine months, the Observatory decided to look for another company capable of making a usable glass circle. In 1975, a contract was awarded to the Heidenhain Corporation of Traunreut, Federal Republic of Germany.

In February 1975, Teledyne-Gurley delivered another glass circle. Like the first one, the circle was a glass sandwich with a silver, diffuse background. A different bonding material was used on this circle. The scans of the circle were excellent and a set of diameter corrections were taken in April of 1975. At this point in time, the six-inch transit circle was well underway in its observing program, measuring only the right ascensions of the objects. The delay caused by the refurbishment of the instrument was already too long, so to halt the observing program in order to wait and see if the circle would degrade was out of the question. The observing program was continued observing the right ascensions and declinations of the objects, on the assumption that this circle would not degrade in quality. Visual inspection of the circle in the months and years to follow showed no deterioration to this circle like that which appeared in the first two Teledyne-Gurley circles. For the first phase of the observing program (a period of about two and a half years) the Teledyne-Gurley circle was used to determine the declinations of the over 23,000 objects observed with the transit circle.

By April of 1976, the Heidenhain Corporation delivered their circle. This circle differed from the Teledyne-Gurley circles in a number of ways. The divisions were deposited on the side nearest the steel wheel using the proprietary DIADUR-MIN method. A thin gold coating was next evaporated over the divisions to provide a smooth, highly reflective mirror background (Fig. 4). This single glass annulus was then bonded to the steel wheel. The Heidenhain Corporation experienced the same difficulty with handling the glass annulus as did Teledyne-Gurley. Scans of this circle were excellent and a first set of diameter corrections were taken in May of 1976.

By the summer of 1977, the first phase of the observing program with the six-inch transit circle was to be completed. For the second part of the program, the USNO planned to use the Heidenhain circle as the primary circle. To check on the stability of this circle another set of diameter corrections was necessary. In February and March of 1977 two sets of diameter corrections were taken on the Heidenhain circle. The Observatory wanted a set of diameter corrections taken during the cold weather to see if temperature had an adverse affect on the circle's stability. A comparison of the three sets of diameter corrections on the circle showed it to be stable. Harmonic analysis showed the differences in the diameter corrections to have no short or long term variation that might not be apparent in the scatter diagrams of the data (Fig. 5). Tests also showed the differences of $\pm 0\overset{''}{.}4$ to be random, and thus likely caused by the noise in the scanner system.

At the completion of the first phase of the six-inch transit circle's observing program in the summer of 1977, two more sets of diameter corrections were taken on the Teledyne-Gurley circle. At that time, new microscope tubes had been installed on the transit circle which proved to be much more stable then the old ones. Also, double scans were taken at every setting so the repeatability of the scanners could be monitored. A comparison of the two sets with the first set showed a large periodic variation in the differences of the diameter corrections (Fig. 6). A harmonic analysis revealed only the long period variation seen in the scatter diagram. The amplitude of the differences was as large as $1\overset{''}{.}44$. Because of the change noted in the Teledyne-Gurley circle, two sets of diameter corrections were taken on the Heidenhain circle. Comparison of these two sets with the other three again showed no change in the circle. The Heidenhain circle was then made the primary circle for the six-inch transit circle and the next phase of the observing program was begun.

Discussion

Since over 23,000 observations depended on the third Teledyne-Gurley circle, the Observatory wanted to be sure the change was real before rejecting the declinations for these observations. Furthermore, if the observations were rejected, the program would have to be extended in order to re-observe those stars.

The manner in which the data was taken helped to show that the cause for the change was circle dependent and not caused by the

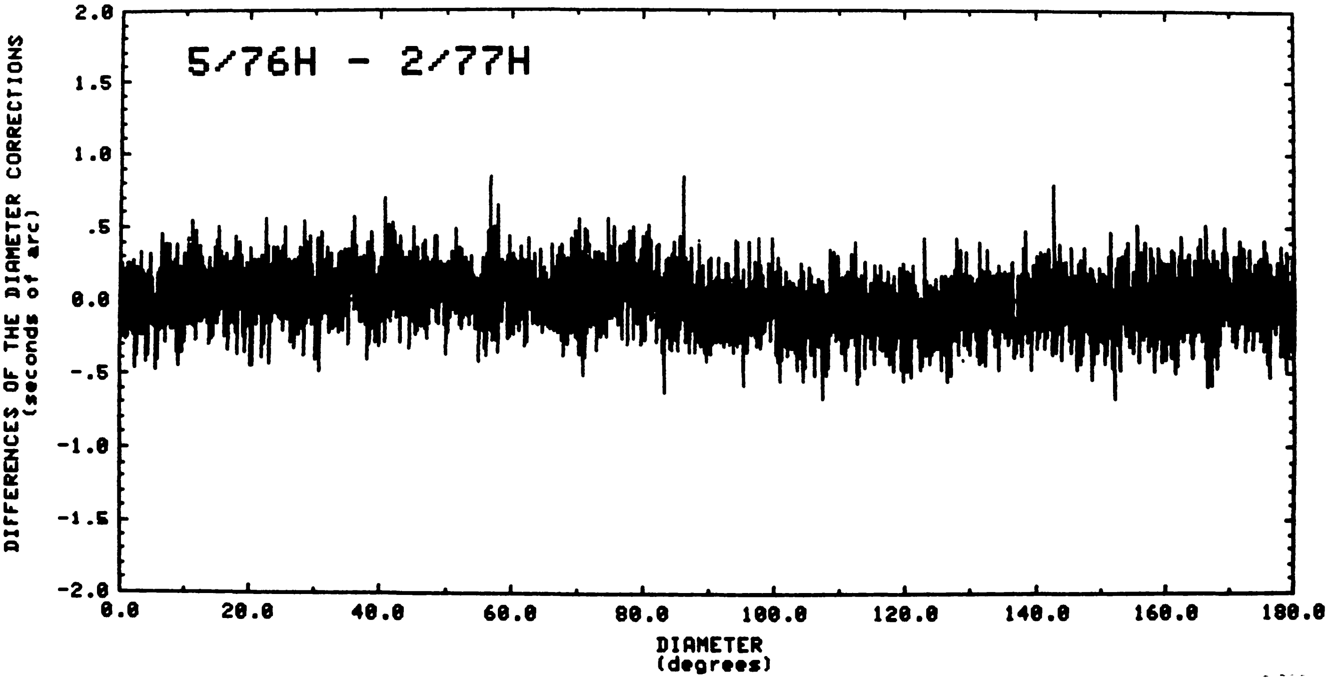

Fig. 5. A scatter diagram of the differences between the April, 1976 (5/76) and February, 1977 (2/77) sets of diameter corrections versus the diameters of the Heidenhain (H) glass circle. The scatter in the data is a result of the random noise in the scanning system

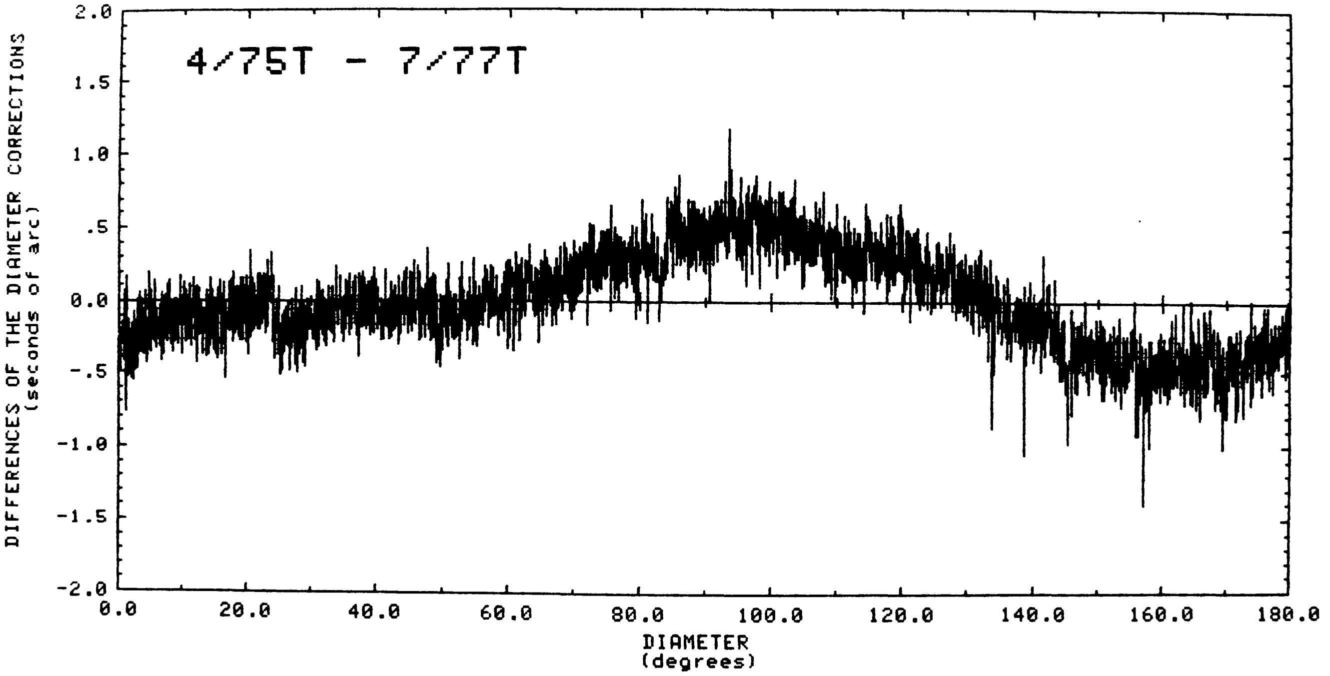

Fig. 6. A scatter diagram of the differences between the April, 1975 and July, 1977 sets of diameter corrections versus the diameters of the third Teledyne-Gurley (T) glass circle. This plot shows the large periodic variation in the differences of the diameter corrections indicating a change in the circle occurred

data taking and reduction methods. The Høg method, used for determining diameter corrections (Høg, 1961) of the glass circles, is comprised of three parts. The main part, the A set, takes measurements of the 3600 diameters of the circle in 240 groups of rosettes. A rosette in the A set is comprised of a group of 15 settings taken 12 degrees apart around the circle. Since there are three independent diameters, and each diameter utilizes two microscopes, there will be 6×15 or a total of 90 readings in each rosette. These readings, when combined with the appropriate coefficients from Høg's method, yield the G-terms, which are generally the

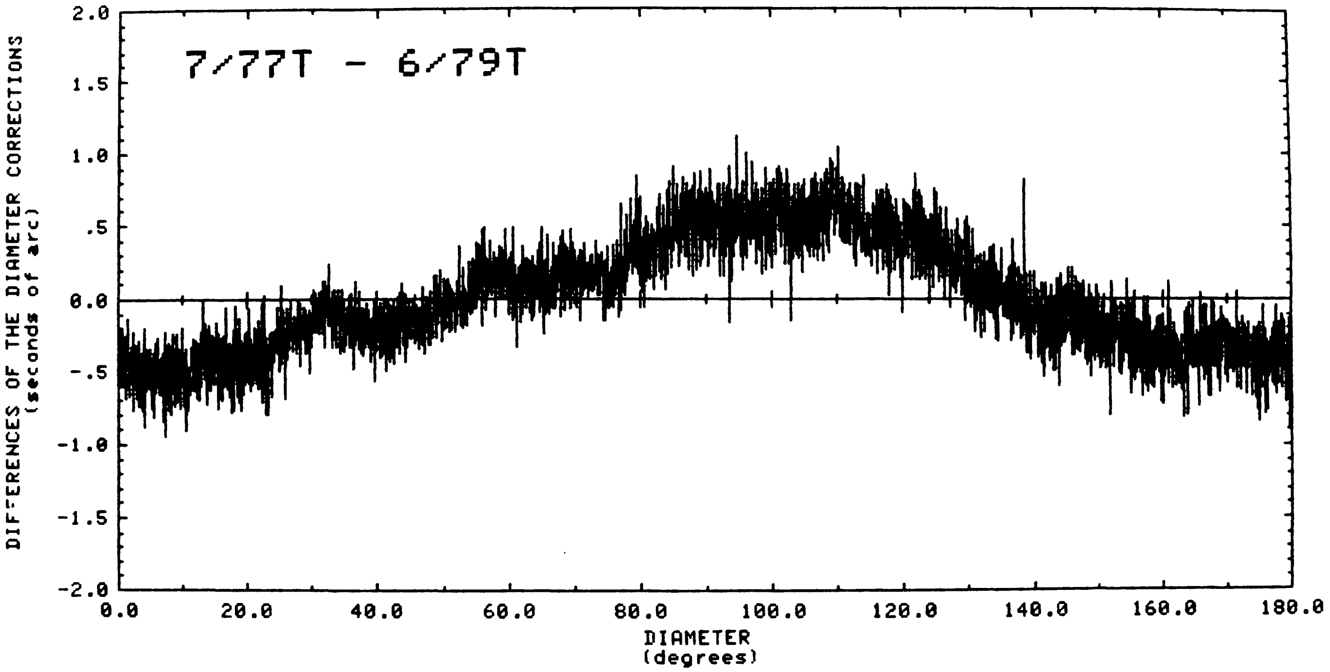

Fig. 7. Scatter diagram of the differences between the first and last set of diameter corrections versus the diameters of the Teledyne-Gurley glass circle. The increase in the amplitude of the differences in the diameter corrections can be seen when compared to Fig. 4 and confirms that the circle continued to change after the July, 1977 set of diameter corrections

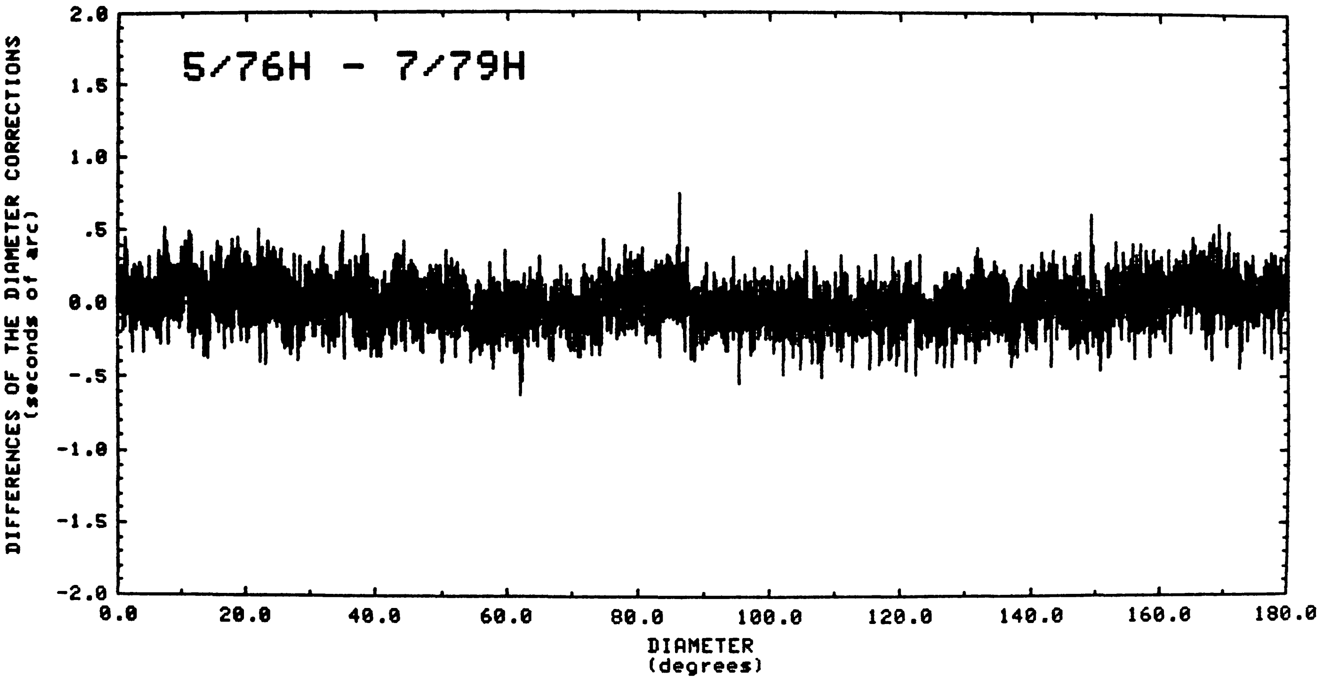

Fig. 8. Scatter diagram of the differences between the first and last taken set of diameter corrections versus the diameters of the Heidenhain glass circle. This shows that the circle did not change in three years

same order of magnitude as the final diameter corrections (E-terms). [The other two parts of the method, the B and C sets, are used to adjust the G-terms (i.e. the "raccordement") to form the final "E-terms" of the diameter corrections.] The large periodic variation in the differences of the E-terms of the Teledyne-Gurley circle could be seen in the differences of the G-terms. Even a comparison of the 15 G-terms from a single rosette showed the change in the circle. This meant that the change was not time dependent within the five day period necessary to gather the data for the A set. Simulated scanner problems and errors in the scales

Table 1. Comparison of the *E*-terms between the various sets of diameter correction determinations. (The sets of diameter corrections are identified by the month/year and *T* for Teledyne-Gurley glass circle or *H* for Heidenhain glass circle)

Sets	Standard Deviation (")	Range Max (")	Min (")
4/75T - 7/77T	.327	1.170	-1.397
4/75T - 9/77T	.336	1.109	-1.444
4/75T - 6/79T	.646	1.681	-1.728
7/77T - 9/77T	.095	.328	-.385
7/77T - 6/79T	.380	1.120	-.943
9/77T - 6/79T	.374	1.206	-.878
5/76H - 2/77H	.207	.860	-.958
5/76H - 3/77H	.198	.846	-.670
5/76H - 7/77H	.157	.990	-.558
5/76H - 8/77H	.145	.878	-.558
5/76H - 7/79H	.165	.752	-.623
2/77H - 3/77H	.194	.792	-.749
2/77H - 7/77H	.173	.742	-.720
2/77H - 8/77H	.172	.724	-.727
2/77H - 7/79H	.179	.634	-.626
3/77H - 7/77H	.142	.601	-.760
3/77H - 8/77H	.143	.637	-.752
3/77H - 7/79H	.160	.893	-.839
7/77H - 8/77H	.087	.464	-.637
7/77H - 7/79H	.116	.727	-.472
8/77H - 7/79H	.109	.727	-.378

of the microscopes on artificial data would not duplicate the periodic variation found in the real data. The only possible cause for the variation appeared to be a change in the glass circle itself.

Since a single rosette could be used to detect a change in the circle, a scheme for monitoring the Heidenhain circle was devised. At six month intervals, the microscopes were aligned to the Høg A set. A subset of the A set made up of ten rosettes was taken and compared with the same rosettes of the earlier full sets of *G*-terms. In this way, unlike the Teledyne-Gurley circle, a change in the circle could be detected before many observations were lost. All of the subsets of *G*-terms taken on the Heidenhain circle, as of this writing, show no change.

If the change in the Teledyne-Gurley circle was abrupt and the time of that change could be pinpointed accurately, the affected observations might be saved. This could be done by applying the appropriate diameter corrections to the observations taken before or after the change in the circle. A scheme of examining the observed minus computed positions (*O–C*'s) of the FK 4 stars was devised. The maximum differences in the determination of the pointing angle error of the transit circle caused by the change in the diameter corrections was calculated. Since the transit circle is reversed every month to help eliminate certain instrumental effects, the pattern of the change as a function of declination for each clamp was different. (Meridian circles engaged in fundamental work rigorously follow the practice of reversing the instrument every lunation. In order to identify which position the instrument is in, it is referenced to the East or West position of the clamp on the horizontal axis.) Also the separation of the six microscopes for the two clamps was different. One clamp had the microscopes set up in the Høg A set configuration; at angles of 0, 24, and 84 deg respectively. The other clamp did not have the same separations of its microscopes. The angles between these microscopes were 0, 55, and 90 deg. The effect of the change in the circle was found to be much greater on the clamp with the microscopes set up in the A set configuration. This arose from the fact that the diameter corrections for that clamp all came from the same rosette, whereas the other clamp obtained its diameter corrections from three different rosettes. This meant that the change in the Teledyne-Gurley circle diameter corrections would cause systematic errors depending on which clamp the telescope was on, which is exactly what reversing the transit circle is supposed to eliminate! (Realizing it was better to break up the pattern as much as possible, the angles between the microscopes on the one clamp were changed to 0, 55, and 90 deg in September, 1977.) The scheme for finding out if the Teledyne-Gurley circle had changed abruptly by using the observations of the FK 4 stars failed to show any sudden step in the *O–C*'s. Little or no effect of the circle change could be seen in the *O–C*'s of the FK 4 stars. It was felt that the change in the Teledyne-Gurley circle may have been gradual and that an effect on the declination of the stars would be difficult, if not impossible, to detect. It was also believed, that even if the effect was small that its systematic nature was unacceptable. The effect would be even greater on the Sun, Moon, and planets where the effect is not minimized by the combining of observations as is done with the final catalogue positions of stars.

It was decided that the only way to confirm positively that the Teledyne-Gurley circle was changing was to wait a period of time and take another set of diameter corrections. In the summer of 1979, sets of diameter corrections were taken on both the Teledyne-Gurley and the Heidenhain circles. The new set on the Teledyne-Gurley circle did, indeed, show the circle to continue to be changing (Fig. 7), although no visual deterioration was ever seen. As a result of knowing that the change in the Teledyne-Gurley circle was real, the 23,000 observations that had been reduced using that circle had to be re-observed. A comparison of the 1979 set of diameter corrections taken on the Heidenhain circle, with the earlier sets, confirmed what the subsets also had shown, that the circle was not changing (Fig. 8). A summary of the standard deviations and range of the differences between all the sets of diameter corrections for both circles are given in Table 1.

In 1981, the USNO awarded another contract to the Heidenhain Corporation to manufacture a second circle for the six-inch transit circle and to install it on the wheel in lieu of the Teledyne-Gurley circle. In the process of removing the glass sandwich of the Teledyne-Gurley circle from the wheel at the USNO, it was noted that the glass was bonded better in some areas than in others. A slippage of the glass in one area of the circle could have caused the effect seen in the differences of the diameter corrections of the Teledyne-Gurley circle.

In December of 1979, another glass circle (70 cm in diameter) was made for the USNO by the Heidenhain Corporation for the seven-inch transit circle. Like the circle for the six-inch transit circle, it had a single glass annulus with a gold background and was bonded to a steel wheel. Heidenhain engineers found that the quality of the glass for the seven-inch transit circle was not as good as that of the first circle manufactured for the six-inch transit circle. Numerous attempts had to be made with glass blanks before finally producing a useable circle. The scanning system for the seven-inch transit circle has not been put on the instrument at the time of this writing, therefore no diameter corrections have been taken. The second circle for the six-inch transit circle arrived at the Observatory in March, 1982. No diameter corrections on that circle have yet been taken. Heidenhain engineers again experienced difficulty with a source of good quality glass and many attempts at making an acceptable circle failed before they finally produced the one recently received.

Conclusions

The quality of the division lines and the uniform background of the glass circles make them superior to the conventional metallic circles. This is of key importance to any automatic circle scanning system. However, the authors would like to emphasize that the manufacture of such a circle is a formidable task. Furthermore, once the circle is in the hands of the user it is mandatory that the circle be monitored for stability.

Acknowledgements. The authors would like to thank Dr. C. A. Smith, Jr. and Mr. E. R. Holdenried for their assistance and valuable discussions during the years that the material for this study was collected.

Reference

Høg, E.: 1961, *Astron. Nachr.* **286**, 65